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The injection and feedback of Cosmic Rays in large-scale structures

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Abstract. We present the numerical implementation of run-time injection of Cosmic Rays energy, their spatial advection and their dynamical feedback on baryonic gas in the cosmological grid code ENZO. We discuss the results of its application to large-scale simulations showing that the CR energy inside clusters of galaxies is small compared to the gas energy (less than a few percent), while the ratio is larger near the accretion regions of clusters and filaments ($\sim 0.1 - 0.3$). CR feedback has a small, but significant impact on the X-ray emission and Sunyaev-Zeldovich effect from clusters.

1. Introduction

The detection of large-scale non-thermal emissions in galaxy clusters proves the existence of magnetic fields and relativistic particles (CR) in the intra cluster medium (e.g. Ferrari et al. 2008). Merger events in clusters drive shock waves in the intra cluster medium, and this can inject primary CR particles and may offer a simple explanation of the observed connection between large-scale radio sources with arc-like shapes (e.g. "radio relics", Brüggen et al. 2011 for a recent review) and the underlying disturbed cluster morphology. The mechanism to convert kinetic energy from the \sim Mpc scale of shock waves into the acceleration of CRs may be explained by the Diffusive Shock Acceleration (DSA, e.g. Bell 1978; Kang & Jones 2007). According to this model, a pool of supra-thermal particles is produced by collision-less shocks in rarefied space plasmas, and are accelerated to higher energies by the interactions with Alfvén waves in the post-shock region. We present our implementation of a model of DSA in the public release of the cosmic code ENZO 1.5 (see Sect.2), simulating the impact of CR physics in the evolution of large-scale structures (see Sect.3).

2. Numerical methods

All simulations presented in this work were performed using the grid-based and adaptive mesh refinement code ENZO (Norman et al. 2007; Collins et al. 2010). ENZO is currently developed by the Laboratory for Computational Astrophysics at the University of California in San Diego (<http://lca.ucsd.edu>). In our work, we implemented the treatment of CR energy injected at shocks by adding several routines,

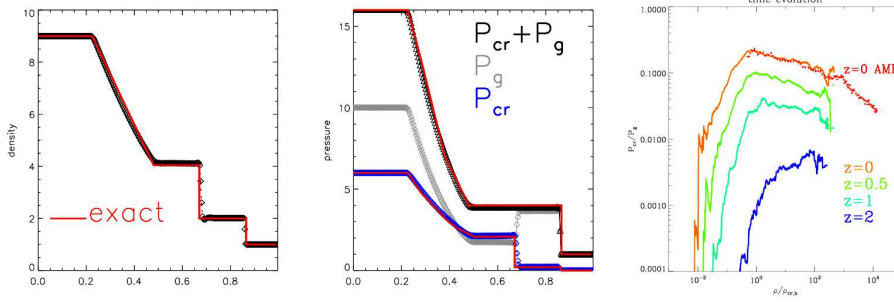


Figure 1. Left and central panel: 1-D shock tube test for an initial mixture of gas and CRs (shown are density, gas, CRs and total pressure). The red lines show the exact solution from Miniati (2007). Right panel: average pressure ratio $P_{\text{cr}}/P_{\text{g}}$ as a function of gas overdensity for a cosmological run at fixed grid resolution ($\Delta x = 156$ kpc/h) for different cosmic epochs. Additionally shown is dotted-red is the result at $z=0$ for an AMR resimulation of a cluster, with a maximum resolution of $\Delta x = 25$ kpc/h.

physical fields and new sets of equations to the public 1.5 release of ENZO, following a two-fluid model approach (e.g. Kang & Jones 2007).

An on-the-fly shock finder was developed to detect shocks in simulations at each time step. This shock finder is based on a 3-D analysis of gas pressure, similar to other methods in the literature (e.g. Ryu et al. 2003; Skillman et al. 2008; Vazza et al. 2009). Once the Mach number, M , is measured, we estimate the total energy flux of accelerated CR protons as: $\phi_{\text{cr}} = \eta(M) \cdot \rho_{\text{u}} v_{\text{s}}^3 / 2$ (ρ_{u} is the pre-shock gas density, v_{s} is the shock velocity, and the function $\eta(M)$ models the efficiency of injection, as in Kang & Jones (2007)). We inject CR energy in each post-shock cell as $E_{\text{cr}} = \phi_{\text{cr}} \Delta t \Delta x^2$, where Δt is the time step and Δx is the cell size; a corresponding amount of energy is also decreased in the post-shock region to conserve total energy. The CR energy is advected with the flow assuming no diffusion and no energy losses for CRs, using an adiabatic index of $\gamma_{\text{cr}} = 4/3$. The total pressure $P = P_{\text{g}} + P_{\text{cr}}$ (where $P_{\text{cr}} = (\gamma_{\text{cr}} - 1)E_{\text{cr}}$ and P_{g} is the gas pressure) is fed into the PPM Riemann solver of ENZO (rather than the gas pressure). The composite fluid gas+CR in the simulation obeys an effective adiabatic index, $\gamma_{\text{eff}} \leq \gamma = 5/3$. To preserve the stability of the method, we also enforce an additional condition on the time step (which avoids too strong a modification of the post-shock during a single time step). For a full description of the adopted methods, and of their tests against analytical solutions we refer the reader to a forthcoming paper (Vazza et al., in prep). In Fig.1, we show the comparison of a 1-D shock tube test and the numerical solution obtained with the Glimm-Godunov's method by Miniati (2007), showing the very good performance of our new scheme.

3. Results

We present here the results of non-radiative cosmological runs for a concordance Λ CDM cosmology, with parameters $\Omega_{\text{dm}} = 0.226$, $\Omega_{\text{b}} = 0.044$ and $\Omega_{\Lambda} = 0.73$; the normalization of the primordial index of density fluctuations was set to $\sigma_8 = 0.8$. In our runs, we used an acceleration efficiency of Kang & Jones (2007); the injection of CR energy is modelled since the start of reionization in the simulated volume (our tests

however suggest that the initial epoch for the injection of CR is not an important parameters, provided that $z_{\text{cr}} \gg 1$). In figure 2 (top panels), we report maps of the spatial distribution of gas and CR pressure for the simulated volume of 80 Mpc at the uniform resolution of 156 kpc/h at $z=0$ (512^3 cells). Despite the overall morphological similarity between thermal gas and CR structures, the CR energy is much more concentrated around large-scale structures than gas energy; this is explained because CRs are injected only in the downstream region of shocks, and because their adiabatic compression during the infall onto collapsed structures is smaller than that of gas, due to their softer equation of state. The average pressure ratio between CRs and gas within the simulated volume has a maximum of $P_{\text{cr}}/P_{\text{g}} \sim 0.2 - 0.3$ at the cosmic gas critical density, and it declines smoothly towards the centre of massive galaxy clusters, approaching $P_{\text{cr}}/P_{\text{g}} \sim 0.05 - 0.1$ there (see right panel in Fig.1). Re-simulations of individual clusters employing adaptive mesh refinement (with maximum resolution of ~ 25 kpc/h) provide an even smaller pressure ratio for the core of clusters, $P_{\text{cr}}/P_{\text{g}} \sim 0.01 - 0.03$ (Fig.2 and right panel of Fig.1). The dynamical role of CR energy is negligible for most of the simulated volume; however, the final distribution of γ_{eff} as a function of radius from the center of structures is not uniform, and decreases towards the outer regions, making the accretion regions of clusters more compressible. This systematically produces a slightly more relaxed matter distribution within clusters, compared to standard runs without CR injection, and this has a small but significant ($\sim 5 - 10$ per cent) impact on the measured X-ray emission profiles and Sunyaev-Zeldovich effect (see Vazza et al. submitted).

4. Conclusions

We presented a numerical development in the grid AMR code ENZO 1.5, which allows us to treat at run-time the injection of CR energy at shocks, their spatial advection and their dynamical (pressure) feedback on the evolution of the baryonic gas. This approach provides an important and complementary approach to similar techniques applied to Smoothed Particles Hydrodynamics methods (e.g. Pfrommer et al. 2006). Simulations employing fixed resolution or adaptive mesh refinement have been run, leading to the detection of small but non-negligible effects respect to standard large-scale structures simulated without CR physics. The application of these techniques to the problem of large-scale non-thermal emission (as for example in radio relics) is underway.

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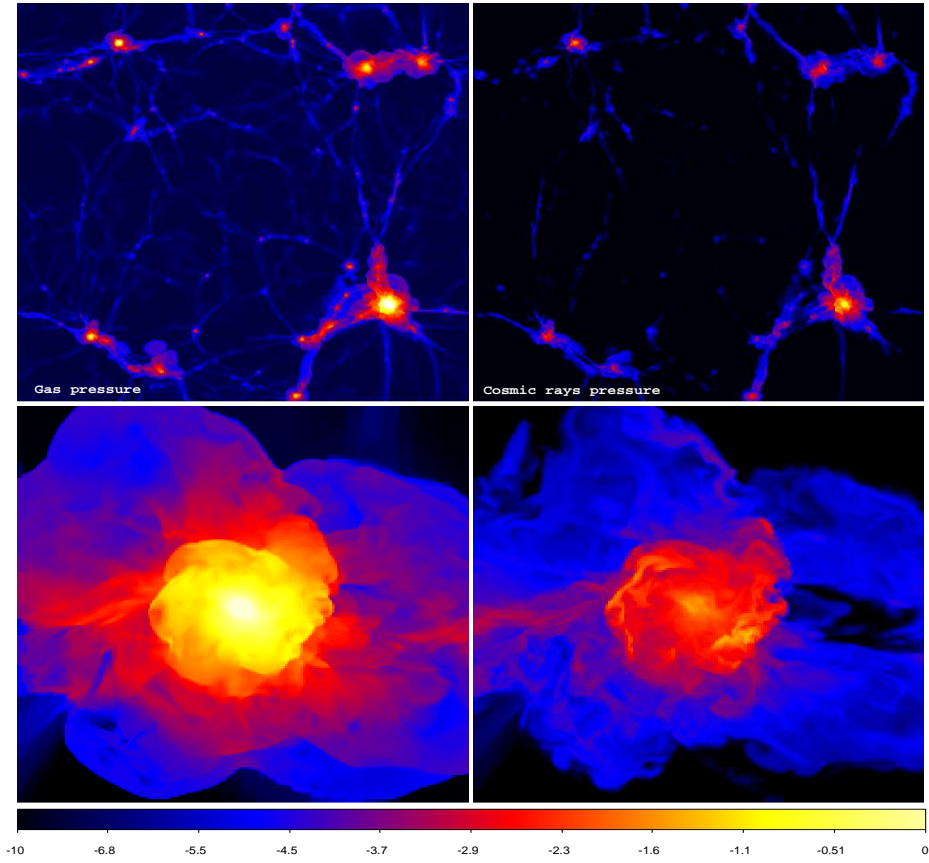


Figure 2. Maps of gas and CR pressure for the simulated volume with the side of 80 Mpc (top panels) and for the AMR resimulation of a galaxy clusters (lower panels, side of 10 Mpc). The color coding is in $\log[\text{arb.units}]$.

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